GPDs and transverse geometry in high-energy ep/pp/pA collisions

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Introduction& DVCS:
M. Diehl - Phys.Rept. 388 (2003),
M. Guidal, H. Moutarde, M. Vanderhaeghen - Rept.Prog.Phys. 76 (2013),
P. Kroll, H. Moutarde, F. Sabatie - Phys. Rev. D87 (2013),
E.-C. Aschenauer, S. Fazio, K. Kumericki, D. Mueller-JHEP 1309 (2013) 093
TCS & NLO & Ultraperipheral:
B. Pire, L. Szymanowski and JW - Phys.Rev. D79 (2009), Phys. Rev. D83 (2011),
D. Mueller, B. Pire, L. Szymanowski and JW - Phys. Rev. D86 (2012),
H. Moutarde, B. Pire, F. Sabatié, L. Szymanowski and JW - Phys. Rev. D87 (2013),
D. Ivanov, L. Szymanowski and JW - in preparation
PARTONS:
B. Berthou, D. Binosi, N. Chouika, M. Guidal, C. Mezrag, H. Moutarde, F. Sabatié, P. Sznajder, J. Wagner - arXiv:1512.06174

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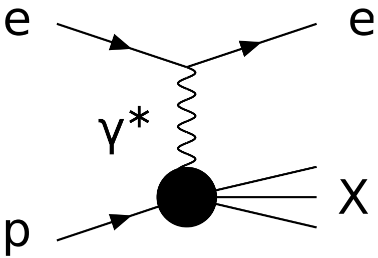
Deep Inelastic Scattering $e\,p \to e\,X$



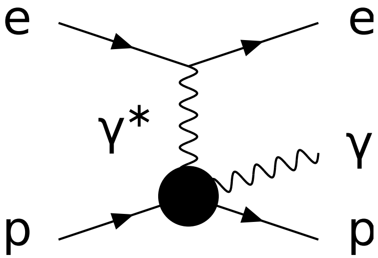
In the Björken limit i.e. when the photon virtality $Q^2 = -q^2$ and the squared hadronic c.m. energy $(p+q)^2$ become large, with the ratio $x_B = \frac{Q^2}{2p\cdot q}$ fixed, the cross section factorizes into a hard partonic subprocess calculable in the perturbation theory, and a parton distributions.

DIS

- Parton distributions encode the distribution of longitudinal momentum and polarization carried by quarks, antiquarks and gluons within fast moving hadron
- PDFs don't provide infomation about how partons are distributed in the transverse plane and ...
- about how important is the orbital angular momentum in making up the total spin of the nucleon.
- Recently - growing interest in the exclusive scattering processes, which may shed some light on these issues through the generalized parton distributions (GPDs) .

DVCS

The simplest and best known process is Deeply Virtual Compton Scattering:
$e\,p \to e\,p\,\gamma$



Factorization into GPDs and perturbative coefficient function - on the level of amplitude.

$$\begin{aligned} \text{DIS}: &\qquad \sigma = \text{PDF} \otimes \text{partonic cross section} \\ \text{DVCS}: &\qquad \mathcal{M} = \text{GPD} \otimes \text{partonic amplitude} \end{aligned}$$

DVCS

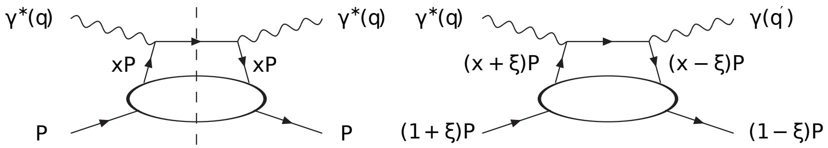


Figure : Deep Inelastic Scattering cross section is given by the imaginary part of diagram (a). Amplitude of Deeply Virtual Compton Scattering is given by diagram (b).

Generalized Bjorken variable:

$$\xi \approx \frac{x_B}{2 - x_B} \quad , \quad x_B = \frac{Q^2}{2q \cdot p}$$

momentum transfer between proton initial and final state:

$$t = (p' - p)^2$$

In the convenient reference frame, where P has only positive time- and z-components, and light vector are defined as:

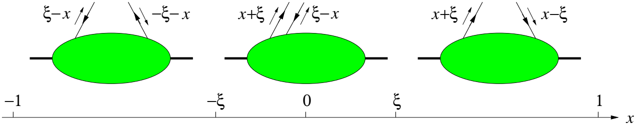
$$v_+ = (1, 0, 0, 1)\frac{1}{\sqrt{2}} \quad , \quad v_- = (1, 0, 0, -1)\frac{1}{\sqrt{2}}$$

(-2ξ) has an interpretation of the fraction of momentum transport in "+" direction.

GPD definition.

$$
\begin{aligned}
F^q &= \frac{1}{2}\int \frac{dz^-}{2\pi}\, e^{ixP^+z^-} \langle p'|\, \bar{q}(-\frac{1}{2}z)\, \gamma^+ q(\frac{1}{2}z)\, |p\rangle \Big|_{z^+=0,\, \mathbf{z}=0} \\
&= \frac{1}{2P^+}\left[H^q(x,\xi,t)\, \bar{u}(p')\gamma^+ u(p) + E^q(x,\xi,t)\, \bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m} u(p) \right], \\
F^g &= \frac{1}{P^+}\int \frac{dz^-}{2\pi}\, e^{ixP^+z^-} \langle p'|\, G^{+\mu}(-\frac{1}{2}z)\, G_\mu{}^+(\frac{1}{2}z)\; |p\rangle \Big|_{z^+=0,\, \mathbf{z}=0} \\
&= \frac{1}{2P^+}\left[H^g(x,\xi,t)\, \bar{u}(p')\gamma^+ u(p) + E^g(x,\xi,t)\, \bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m} u(p) \right],
\end{aligned}
$$

- interpretation, ERBL, DGLAP



- Three variables x, ξ, t .

GPD - properties,

- Forward limit:

$$
\begin{aligned}
H^q(x,0,0) &= q(x)\,, \qquad \text{for} \qquad x>0\,,\\
H^q(x,0,0) &= -\bar{q}(x)\,, \qquad \text{for} \qquad x<0\,,\\
H^g(x,0,0) &= xg(x)\,,
\end{aligned}
$$

similarly for polarized distributions and PDFs.

- Reduction to form factors:

$$
\int_{-1}^{1} dx\, H^q(x,\xi,t) = F_1^q(t), \qquad \int_{-1}^{1} dx\, E^q(x,\xi,t) = F_2^q(t),
$$

where the Dirac and Pauli form factors

$$
\langle p' |\, \bar{q}(0)\gamma^\mu q(0)\, |p\rangle = \bar{u}(p') \left[F_1^q(t)\,\gamma^\mu + F_2^q(t)\,\frac{i\sigma^{\mu\alpha}\Delta_\alpha}{2m} \right] u(p),
$$

- Ji sum rule:

$$
\lim_{t\to 0} \int_{-1}^{1} dx\; x\,[H_f(x,\xi,t) + E_f(x,\xi,t)] = 2J_f
$$

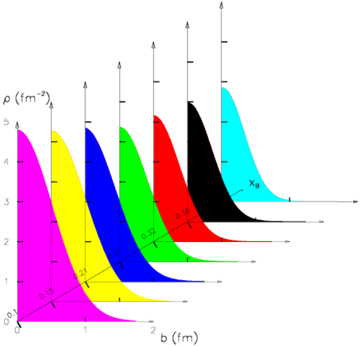
where J_f is fraction of the proton spin carried by quark f (including spin and orbital angular momentum).

Impact parameter representation

At $\xi = 0 \qquad \Rightarrow \qquad -t = \Delta_\perp^2$:

$$H(x, \mathbf{b}_\perp) = \int \frac{d^2\mathbf{\Delta}_\perp}{(2\pi)^2} e^{-i\mathbf{b}_\perp \cdot \mathbf{\Delta}_\perp} H(x, 0, -\mathbf{\Delta}_\perp)$$

can be interpreted as probability of finding a parton with longitudinal momentum fraction x at a given $\mathbf{b}_\perp$.

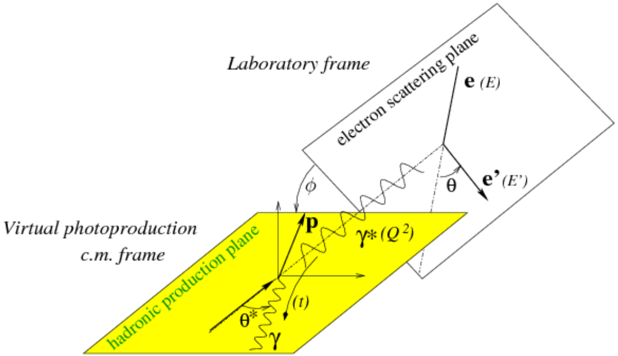


GPDs

- GPDs enter factorization theorems for hard exclusive reactions (DVCS, deeply virtual meson production, TCS etc.), in a similar manner as PDFs enter factorization theorems for inclusive (DIS, etc.)
- GPDs are functions of x, t, ξ, μ_F^2
- First moment of GPDs enters the Ji's sum rule for the angular momentum carried by partons in the nucleon,
- 2+1 imaging of nucleon,
- Deeply Virtual Compton Scattering (DVCS) is a golden channel for GPDs extraction,

DVCS - variables

Four variables needed to describe $ep \longrightarrow ep\gamma$ at fixed beam energy. Usually : Q^2, x_B, t and ϕ:



Coefficient functions and Compton Form Factors

CFFs are the GPD dependent quantities which enter the amplitudes. They are defined through relations:

$$\mathcal{A}^{\mu\nu}(\xi,t) = -e^2 \frac{1}{(P+P')^+}\,\bar{u}(P')\left[g_T^{\mu\nu}\left(\mathcal{H}(\xi,t)\,\gamma^+ + \mathcal{E}(\xi,t)\,\frac{i\sigma^{+\rho}\Delta_\rho}{2M}\right) + i\epsilon_T^{\mu\nu}\left(\widetilde{\mathcal{H}}(\xi,t)\,\gamma^+\gamma_5 + \widetilde{\mathcal{E}}(\xi,t)\,\frac{\Delta^+\gamma_5}{2M}\right)\right]u(P)\,,$$

,where:

$$\mathcal{H}(\xi,t) \quad = \quad +\int_{-1}^{1} dx \left(\sum_q T^q(x,\xi)H^q(x,\xi,t) + T^g(x,\xi)H^g(x,\xi,t)\right)$$

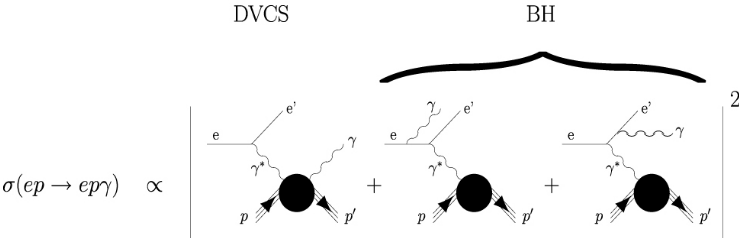
GPDs enter through convolutions! At LO in α_S:

$${}^{DVCS}T^q = -e_q^2 \frac{1}{x+\xi-i\varepsilon} - (x \to -x)$$

$${}^{DVCS}Re(\mathcal{H}) \sim P\int \frac{1}{x+\xi}H^q(x,\xi,t)\,, \qquad {}^{DVCS}Im(\mathcal{H}) \sim i\pi H^q(\xi,\xi,t)$$

DVCS and BH

Figure 12 from Michel Guidal et al 2013 Rep. Prog. Phys. 76 066202



Observables

The $lp \to lp\gamma$ cross section on an unpolarized target for a given beam charge e_l and beam helicity $h_l/2$:

$$d\sigma^{h_l,e_l}(\phi) = d\sigma_{\mathrm{UU}}(\phi)\left[1 + h_l A_{\mathrm{LU,DVCS}}(\phi) + e_l h_l A_{\mathrm{LU,I}}(\phi) + e_l A_{\mathrm{C}}(\phi)\right] ,$$

In HERMES - both longitudinally polarized positively and negatively charged beams were available:

$$A_{\mathrm{C}}(\phi) = \frac{1}{4d\sigma_{\mathrm{UU}}(\phi)}\left[\left(d\sigma^{\overset{+}{\rightarrow}} + d\sigma^{\overset{+}{\leftarrow}}\right) - \left(d\sigma^{\overset{-}{\rightarrow}} + d\sigma^{\overset{-}{\leftarrow}}\right)\right] .$$

$$\begin{aligned} A_{\mathrm{LU,I}}(\phi) &= \frac{1}{4d\sigma_{\mathrm{UU}}(\phi)}\left[\left(d\sigma^{\overset{+}{\rightarrow}} - d\sigma^{\overset{+}{\leftarrow}}\right) - \left(d\sigma^{\overset{-}{\rightarrow}} - d\sigma^{\overset{-}{\leftarrow}}\right)\right] , \\ A_{\mathrm{LU,DVCS}}(\phi) &= \frac{1}{4d\sigma_{\mathrm{UU}}(\phi)}\left[\left(d\sigma^{\overset{+}{\rightarrow}} - d\sigma^{\overset{+}{\leftarrow}}\right) + \left(d\sigma^{\overset{-}{\rightarrow}} - d\sigma^{\overset{-}{\leftarrow}}\right)\right] . \end{aligned}$$

In Jefferson Lab, one can only measure the beam spin asymmetry $A_{\mathrm{LU}}^{e_l}$

$$A_{\mathrm{LU}}^{e_l}(\phi) = \frac{d\sigma^{\overset{e_l}{\rightarrow}} - d\sigma^{\overset{e_l}{\leftarrow}}}{d\sigma^{\overset{e_l}{\rightarrow}} + d\sigma^{\overset{e_l}{\leftarrow}}} ,$$

Observables

Target longitudinal spin asymmetry which reads :

$$A_{\mathrm{UL}}^{e_l}(\phi) = \frac{[d\sigma^{\overset{e_l}{\leftarrow\Rightarrow}} + d\sigma^{\overset{e_l}{\rightarrow\Rightarrow}}] - [d\sigma^{\overset{e_l}{\leftarrow\Leftarrow}} + d\sigma^{\overset{e_l}{\rightarrow\Leftarrow}}]}{[d\sigma^{\overset{e_l}{\leftarrow\Rightarrow}} + d\sigma^{\overset{e_l}{\rightarrow\Rightarrow}}] + [d\sigma^{\overset{e_l}{\leftarrow\Leftarrow}} + d\sigma^{\overset{e_l}{\rightarrow\Leftarrow}}]},$$

where the double arrows $\Leftarrow$ ($\Rightarrow$) refer to the target polarization state parallel (anti-parallel) to the beam momentum. The double longitudinal target spin asymmetry is defined in a similar fashion :

$$A_{\mathrm{LL}}^{e_l}(\phi) = \frac{[d\sigma^{\overset{e_l}{\rightarrow\Rightarrow}} + d\sigma^{\overset{e_l}{\leftarrow\Leftarrow}}] - [d\sigma^{\overset{e_l}{\leftarrow\Rightarrow}} + d\sigma^{\overset{e_l}{\rightarrow\Leftarrow}}]}{[d\sigma^{\overset{e_l}{\rightarrow\Rightarrow}} + d\sigma^{\overset{e_l}{\leftarrow\Leftarrow}}] + [d\sigma^{\overset{e_l}{\leftarrow\Rightarrow}} + d\sigma^{\overset{e_l}{\rightarrow\Leftarrow}}]},$$

The HERMES collaboration also had access to a transversally polarized target with both electrons and positrons:

$$\begin{aligned}
A_{\mathrm{UT,I}}(\phi,\phi_S) &= \\
&\frac{d\sigma^+(\phi,\phi_S) + d\sigma^+(\phi,\phi_S+\pi) - d\sigma^-(\phi,\phi_S) - d\sigma^-(\phi,\phi_S+\pi)}{d\sigma^+(\phi,\phi_S) - d\sigma^+(\phi,\phi_S+\pi) + d\sigma^-(\phi,\phi_S) - d\sigma^-(\phi,\phi_S+\pi)}, \\
A_{\mathrm{UT,DVCS}}(\phi,\phi_S) &= \\
&\frac{d\sigma^+(\phi,\phi_S) - d\sigma^+(\phi,\phi_S+\pi) - d\sigma^-(\phi,\phi_S) + d\sigma^-(\phi,\phi_S+\pi)}{d\sigma^+(\phi,\phi_S) - d\sigma^+(\phi,\phi_S+\pi) + d\sigma^-(\phi,\phi_S) - d\sigma^-(\phi,\phi_S+\pi)}
\end{aligned}$$

Observables

$$
\begin{aligned}
A_C^{\cos\phi} &\propto \mathrm{Re}\left[F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - \frac{t}{4m^2}F_2\mathcal{E}\right], \\
A_{LU,I}^{\sin\phi} &\propto \mathrm{Im}\left[F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - \frac{t}{4m^2}F_2\mathcal{E}\right], \\
A_{UL,I}^{\sin\phi} &\propto \mathrm{Im}\left[\xi(F_1+F_2)(\mathcal{H} + \frac{\xi}{1+\xi}\mathcal{E}) + F_1\widetilde{\mathcal{H}} - \xi(\frac{\xi}{1+\xi}F_1 + \frac{t}{4M^2}F_2)\widetilde{\mathcal{E}}\right], \\
A_{LL,I}^{\cos\phi} &\propto \mathrm{Re}\left[\xi(F_1+F_2)(\mathcal{H} + \frac{\xi}{1+\xi}\mathcal{E}) + F_1\widetilde{\mathcal{H}} - \xi(\frac{\xi}{1+\xi}F_1 + \frac{t}{4M^2}F_2)\widetilde{\mathcal{E}}\right], \\
A_{LL,DVCS}^{\cos(0\phi)} &\propto \mathrm{Re}\Big[4(1-\xi^2)\big(\mathcal{H}\widetilde{\mathcal{H}}^* + \widetilde{\mathcal{H}}\mathcal{H}^*\big) - 4\xi^2\big(\mathcal{H}\widetilde{\mathcal{E}}^* + \widetilde{\mathcal{E}}\mathcal{H}^* + \widetilde{\mathcal{H}}\mathcal{E}^* + \mathcal{E}\widetilde{\mathcal{H}}^*\big) \\
&\qquad -4\xi(\frac{\xi^2}{1+\xi} + \frac{t}{4M^2})\,\big(\mathcal{E}\widetilde{\mathcal{E}}^* + \widetilde{\mathcal{E}}\mathcal{E}^*\big)\Big], \\
A_{UT,DVCS}^{\sin(\phi-\phi_s)} &\propto \left[\mathrm{Im}\,(\mathcal{H}\mathcal{E}^*) - \xi\mathrm{Im}\,(\widetilde{\mathcal{H}}\widetilde{\mathcal{E}}^*)\right], \\
A_{UT,I}^{\sin(\phi-\phi_s)\cos\phi} &\propto \mathrm{Im}\Big[-\frac{t}{4M^2}\big(F_2\mathcal{H} - F_1\mathcal{E}\big) + \xi^2\big(F_1 + \frac{t}{4M^2}F_2\big)\big(\mathcal{H}+\mathcal{E}\big) \\
&\qquad -\xi^2\big(F_1+F_2\big)\big(\widetilde{\mathcal{H}} + \frac{t}{4M^2}\widetilde{\mathcal{E}}\big)\Big].
\end{aligned}
\tag{1}
$$

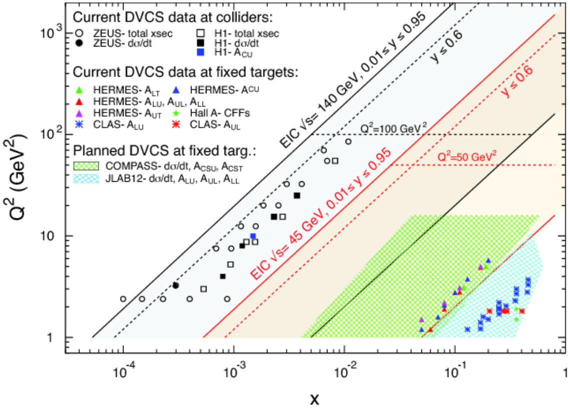
Models

Topic for another seminar...

- A lot of data, but not enough to fit 4 GPDs (function of 3 variables) for every quark flavour ... and gluons
- GPDs must satisfy certain principles
- Few models on the market (Goloskokov-Kroll, VGG, Kumericki-Mueller ...), most of them describe data well, only one describes all data - including small x.
- still much more data needed to determine GPDs (only imaginary part of CFF H determined with 15% precision, rest unconstrained)

FUTURE

- JLAB - 12 GeV . Plans for Hall A and CLAS to measure beam spin and target spin asymmetries with much higher luminosity, smaller x_B and higher Q^2. Also CLAS plan to measure DVCS on neutron - necessary to make GPD flavour separation.
- COMPASS - recoil detector to ensure exclusivity - plans to measure mixed charge-spin asymmetries with $160\,\mathrm{GeV}$ muon beam.
- EIC (!)



DVCS - JLab : beam spin asymmetry

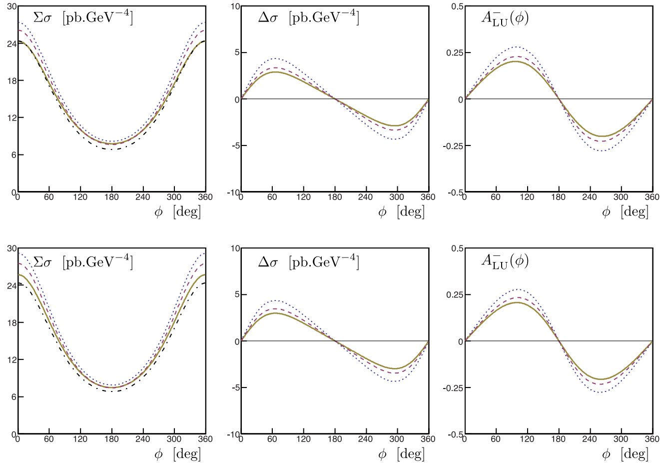
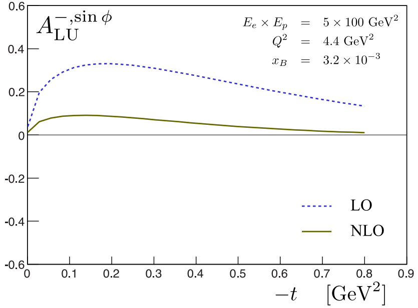


Figure : $E_e = 11\,\mathrm{GeV}, \mu_F^2 = Q^2 = 4$ GeV^2 and $t = -0.2$ GeV^2. On the first line, the GPD $H(x,\xi,t)$ is parametrized by the GK model, on the second line by factorized model based on the MSTW08 parametrization. The contributions from other GPDs are not included. In all plots, the LO - dotted line, the full NLO - solid line, NLO result without the gluonic contribution - dashed line, the BH- dashdotted line.

DVCS - EIC: beam spin asymmetry A_{LU}



$$A_{LU}^{\sin\phi} \propto \mathrm{Im}\left[F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - \frac{t}{4m^2}F_2\mathcal{E}\right]$$

Compton Form Factors - DVCS - $Im(\mathcal{H})$

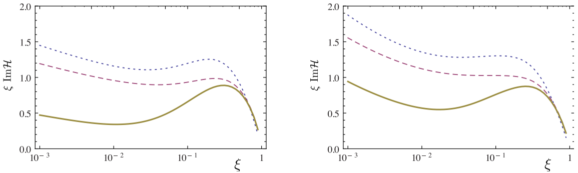
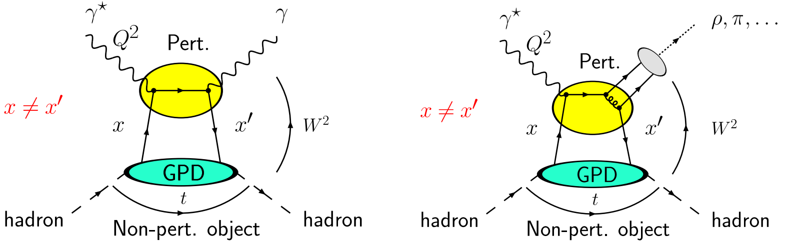


Figure : The imaginary part of the *spacelike* Compton Form Factor $\mathcal{H}(\xi)$ multiplied by ξ, as a function of ξ in the double distribution model based on Kroll-Goloskokov (upper left) and MSTW08 (upper right) parametrizations, for $\mu_F^2 = Q^2 = 4\,\mathrm{GeV}^2$ and $t = -0.1\,\mathrm{GeV}^2$, at the Born order (dotted line), including the NLO quark corrections (dashed line) and including both quark and gluon NLO corrections (solid line).

DVCS - what else, and why

- Difficult: exclusivity, 3 variables, GPD enter through convolutions, only GPD(ξ, ξ, t) accesible through DVCS at LO!
- universality,
- flavour separation,



- Meson production - additional information (and difficulties),

So, in addition to spacelike DVCS ...

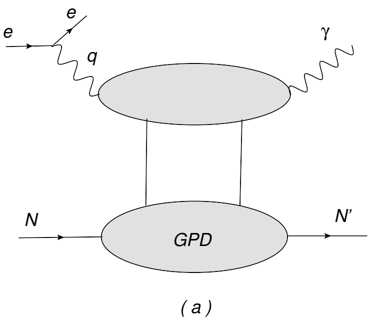


Figure : Deeply Virtual Compton Scattering (DVCS) : $lN \to l'N'\gamma$

we can also study timelike DVCS

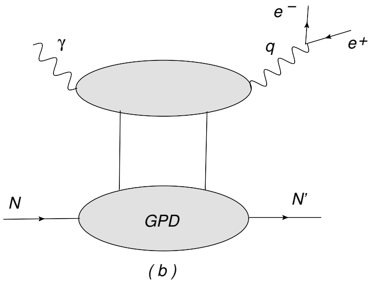


Figure : Timelike Compton Scattering (TCS): $\gamma N \to l^+ l^- N'$

Why TCS:

- universality of the GPDs
- another source for GPDs (special sensitivity on real part of GPD H),
- spacelike-timelike crossing,
- first step towards DDCVS,

Coefficient functions and Compton Form Factors

- DVCS vs TCS - LO

$$
\begin{aligned}
{}^{DVCS}T^q &= -e_q^2 \frac{1}{x+\eta-i\varepsilon} - (x \to -x) = \quad \left({}^{TCS}T^q\right)^* \\
{}^{DVCS}\tilde{T}^q &= -e_q^2 \frac{1}{x+\eta-i\varepsilon} + (x \to -x) = \quad -\left({}^{TCS}\tilde{T}^q\right)^*
\end{aligned}
$$

$$
{}^{DVCS}Re(\mathcal{H}) \sim P \int \frac{1}{x \pm \eta} H^q(x,\eta,t)\,, \qquad {}^{DVCS}Im(\mathcal{H}) \sim i\pi H^q(\pm\eta,\eta,t)
$$

- NLO Renormalized coefficient functions for DVCS are given by

$$
\begin{aligned}
T^q(x) &= \left[C_0^q(x) + C_1^q(x) + \ln\left(\frac{Q^2}{\mu_F^2}\right) \cdot C_{coll}^q(x)\right] - (x \to -x)\,, \\
T^g(x) &= \left[C_1^g(x) + \ln\left(\frac{Q^2}{\mu_F^2}\right) \cdot C_{coll}^g(x)\right] + (x \to -x)\,,
\end{aligned}
$$

The results for DVCS and TCS cases are simply related:

$$
{}^{TCS}T(x,\eta) = \pm\left({}^{DVCS}T(x,\xi=\eta) + i\pi \cdot C_{coll}(x,\xi=\eta)\right)^*\,,
$$

D.Mueller, B.Pire, L.Szymanowski, J.Wagner, Phys.Rev.D86, 2012.

where $+$ $(-)$ sign corresponds to vector (axial) case.

TCS and Bethe-Heitler contribution to exclusive lepton pair photoproduction.

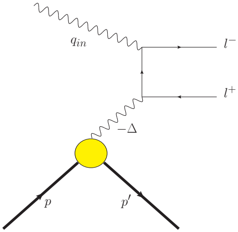


Figure : The Feynman diagram for the Bethe-Heitler amplitude.

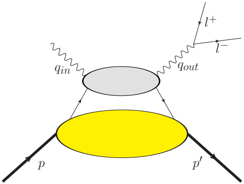


Figure : The Feynman diagram for the Compton amplitude.

TCS

Berger, Diehl, Pire, 2002

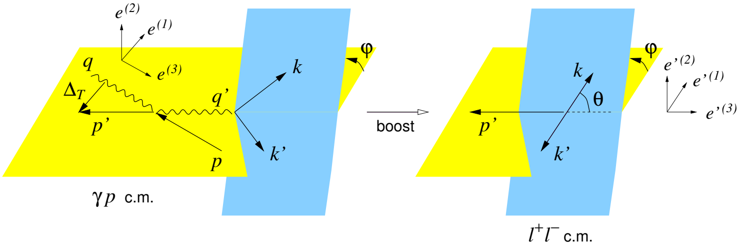


Figure : Kinematical variables and coordinate axes in the γp and $\ell^+\ell^-$ c.m. frames.

Interference

B-H dominant for not very high energies:

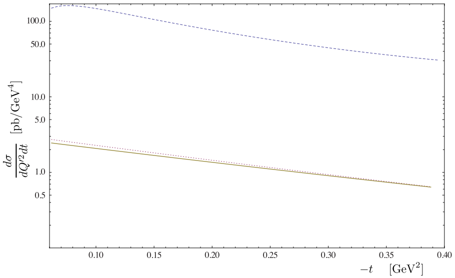


Figure : LO (dotted) and NLO (solid) TCS and Bethe-Heitler (dash-dotted) contributions to the cross section as a function of t for $Q^2 = \mu^2 = 4\,\mathrm{GeV}^2$ integrated over $\theta \in (\pi/4; 3\pi/4)$ and over $\phi \in (0; 2\pi)$ for $E_\gamma = 10\,\mathrm{GeV} (\eta \approx 0.11)$.

The interference part of the cross-section for $\gamma p \to \ell^+ \ell^- \, p$ with unpolarized protons and photons is given by:

$$\frac{d\sigma_{INT}}{dQ'^2\, dt\, d\cos\theta\, d\varphi} \sim \cos\varphi \cdot \; \mathrm{Re}\,\mathcal{H}(\eta, t)$$

Linear in GPD's, odd under exchange of the l^+ and l^- momenta $\Rightarrow$ angular distribution of lepton pairs is a good tool to study interference term.

JLAB 6 GeV data and a future experiments with 12 GeV

Rafayel Paremuzyan PhD thesis

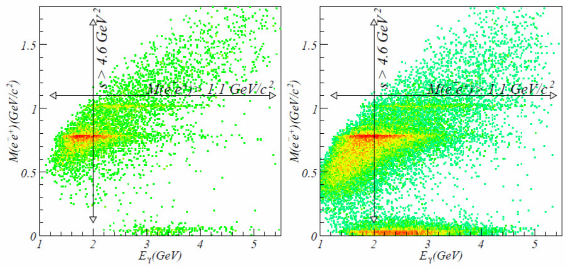
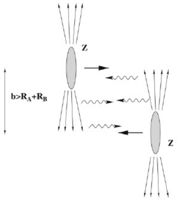


Figure : e^+e^- invariant mass distribution vs quasi-real photon energy. For TCS analysis $M(e^+e^-) > 1.1\,\mathrm{GeV}$ and $s_{\gamma p} > 4.6\,\mathrm{GeV}^2$ regions are chosen. Left graph represents e1-6 data set, right one is from e1f data set.

Approved experiment at CLAS12, SoLID. LOI for transversely polarized target, plans for linearly polarized photons in CLAS12.

Ultraperipheral collisions



$$\sigma = \int \frac{dn(k)}{dk} \sigma_{\gamma p}(k) dk$$

$\sigma_{\gamma p}(k)$ is the cross section for the $\gamma p \to p l^+ l^-$ process and k is the γ's energy, and $\frac{dn(k)}{dk}$ is an equivalent photon flux.

$$\frac{dn}{dk} = \frac{2Z^2 \alpha_{EM}}{\pi k} \left[\omega^{pA} K_0(\omega^{pA}) K_1(\omega^{pA}) - \frac{\omega^{pA^2}}{2} \left(K_1^2(\omega^{pA}) - K_0^2(\omega^{pA}) \right) \right] \quad (2)$$

The TCS differential cross section at UPC

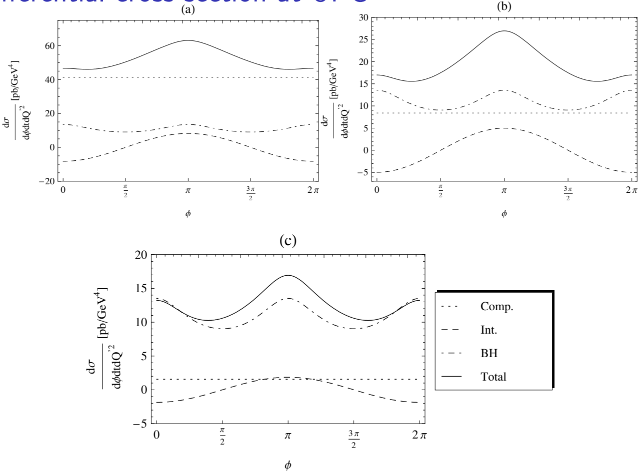


Figure : The differential cross sections (solid lines) for $t = -0.2\,\mathrm{GeV}^2$, $Q'^2 = 5\,\mathrm{GeV}^2$ and integrated over $\theta = [\pi/4, 3\pi/4]$, as a function of φ, for $s = 10^7\,\mathrm{GeV}^2$ (a), $s = 10^5\,\mathrm{GeV}^2$(b), $s = 10^3\,\mathrm{GeV}^2$ (c) with $\mu_F^2 = 5\,\mathrm{GeV}^2$. We also display the Compton (dotted), Bethe-Heitler (dash-dotted) and Interference (dashed) contributions.

Gluon GPDs in the UPC production of heavy mesons

Work in progress with D.Yu.Ivanov and L.Szymanowski

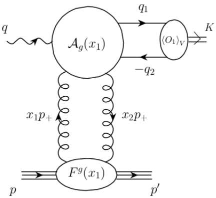


Figure 1: Kinematics of heavy vector meson photoproduction.

D. Yu. Ivanov , A. Schafer , L. Szymanowski and G. Krasnikov - **Eur.Phys.J. C34 (2004) 297-316**

The amplitude $\mathcal{M}$ is given by factorization formula:

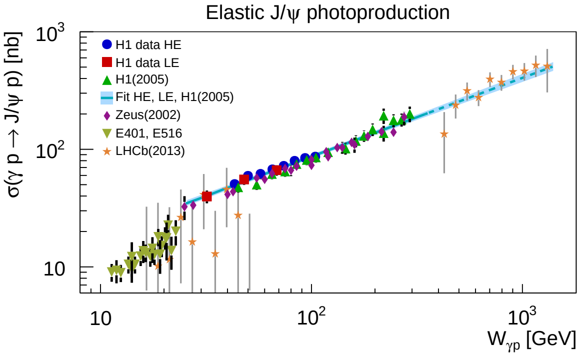
$$\mathcal{M} \sim \left(\frac{\langle O_1\rangle_V}{m^3}\right)^{1/2} \int\limits_{-1}^{1} dx \left[T_g(x,\xi)\, F^g(x,\xi,t) + T_q(x,\xi) F^{q,S}(x,\xi,t) \right] ,$$

$$F^{q,S}(x,\xi,t) = \sum_{q=u,d,s} F^q(x,\xi,t) .$$

where m is a pole mass of heavy quark, $\langle O_1\rangle_V$ is given by NRQCD through leptonic meson decay rate.

Heavy Vector Mesons Photoproduction

We have good data! See H1 2013 paper:



Photoproduction cross section - LO and NLO

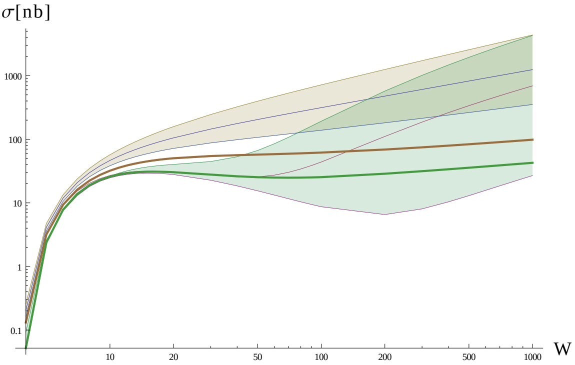
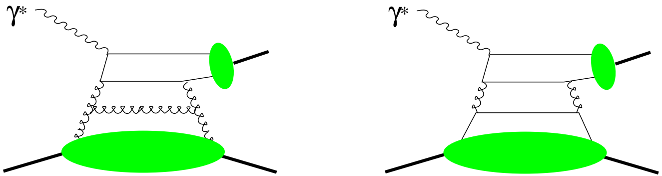


Figure : Photoproduction cross section as a function of $W = \sqrt{s_{\gamma p}}$ for $\mu_F^2 = M_{J/\psi}^2 \times \{0.5, 1, 2\}$- LO and NLO. Thick lines for LO and NLO for $\mu_F^2 = 1/4 M_{J/\psi}^2$.

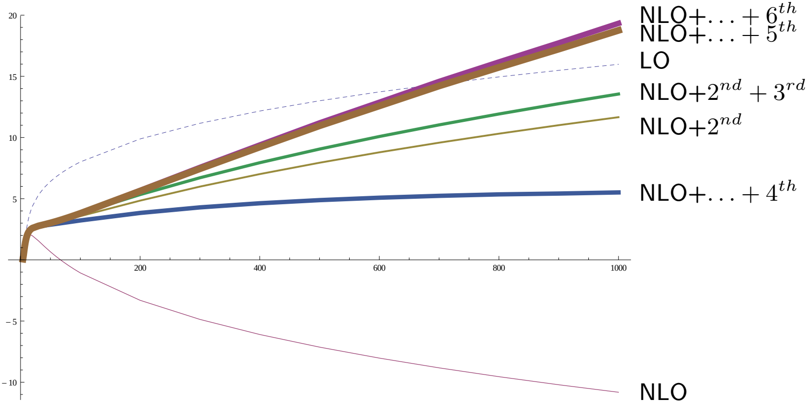
- Jones & Martin & Ryskin & Teubner, arXiv:1507.06942. Choice of the factorization scale.
- Why NLO corrections are large at small x_B?
  large contribution comes from

$$ImA^g \sim H^g(\xi,\xi) + \frac{3\alpha_s}{\pi}\left[\log\frac{M_V^2}{\mu_F^2} - \log 4\right]\int_{\xi}^{1}\frac{dx}{x}H^g(x,\xi)$$

$H^g(x,\xi) \sim xg(x) \sim const$, therefore $\int dx/x H^g(x,\xi) \sim \log(1/\xi) H^g(\xi,\xi)$



Resummed amplitude for J/ψ



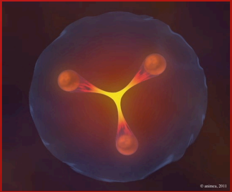
Imaginary part of the amplitude for photoproduction of heavy mesons as a function of $W = \sqrt{s_{\gamma p}}$ for $\mu_F^2 = M_{J/\psi}^2$

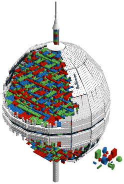
Summary

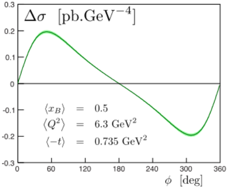
- GDPs enter factorization theorems for hard exclusive reactions (DVCS, deeply virtual meson production etc.), in a similar manner as PDFs enter factorization theorem for DIS
- First moment of GPDs enter the Ji's sum rule for the angular momentum carried by partons in the nucleon.
- Fourier transform of GPD's to impact parameter space can be interpreted as „tomographic" 3D pictures of nucleon, describing charge distribution in the transverse plane, for a given value of x.
- A lot of data on DVCS, but not enough to determine GPDs,
- A lot of new experiments planned to measure DVCS - JLAB 12, COMPASS, EIC,
- Timelike-DVCS is a complementary measurement,
- TCS already measured at JLAB 6 GeV, but much richer and more interesting kinematical region available after upgrade to 12 GeV,
- Compton scattering and heavy vector meson production in ultraperipheral collisions at hadron colliders opens a new way to measure generalized parton distributions,
- NLO corrections very important, also important for GPD extraction at $\xi \neq x$.

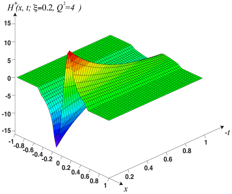
DE LA RECHERCHE À L'INDUSTRIE

PARTONS platform version 1









Highlight January 2016 | Hervé MOUTARDE

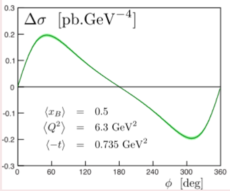
January 7$^{\text{th}}$, 2016

www.cea.fr

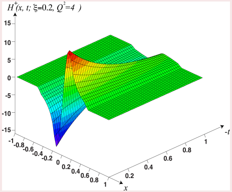
Proton imaging. How ?

From theory to experimental data

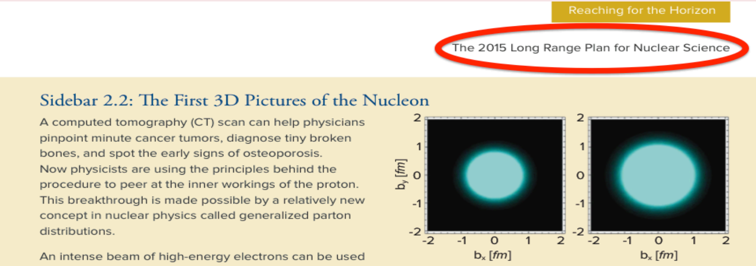
1. Data fitting



2. Parton distributions



3. Imaging - Review Guidal-Moutarde-Vanderhaeghen (2013)


Reaching for the Horizon

The 2015 Long Range Plan for Nuclear Science

Sidebar 2.2: The First 3D Pictures of the Nucleon

A computed tomography (CT) scan can help physicians pinpoint minute cancer tumors, diagnose tiny broken bones, and spot the early signs of osteoporosis. Now physicists are using the principles behind the procedure to peer at the inner workings of the proton. This breakthrough is made possible by a relatively new concept in nuclear physics called generalized parton distributions.

An intense beam of high-energy electrons can be used

Joint analysis of worldwide data

Towards high precision phenomenology

PARTONSv1

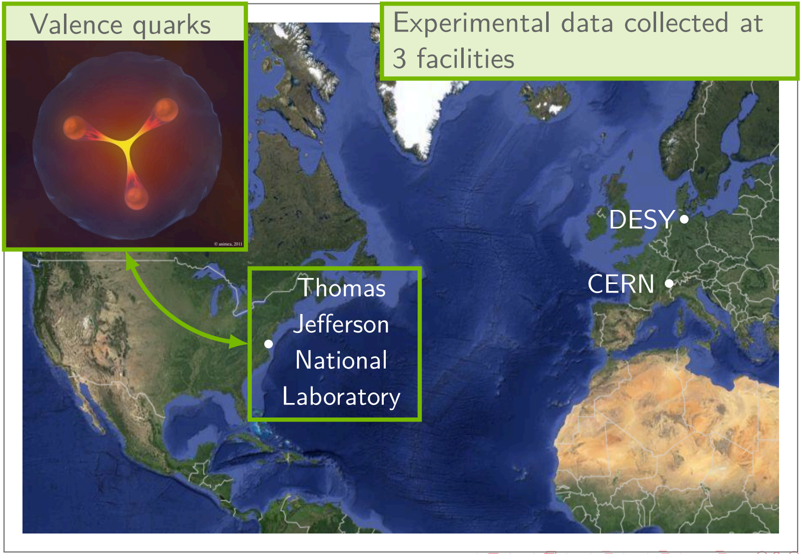
Contexte

PARTONS Project

Experimental data collected at 3 facilities

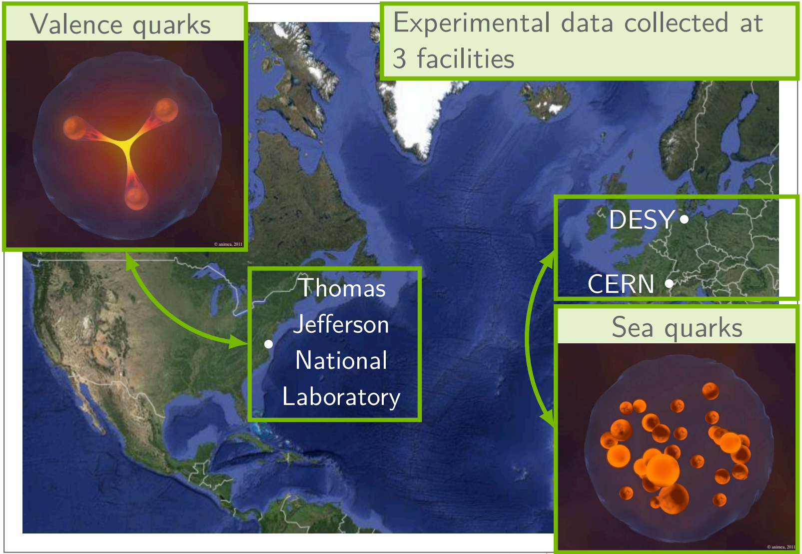
Joint analysis of worldwide data

Towards high precision phenomenology



Joint analysis of worldwide data

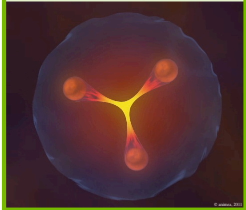
Towards high precision phenomenology



Joint analysis of worldwide data

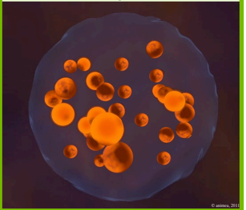
Towards high precision phenomenology

Valence quarks



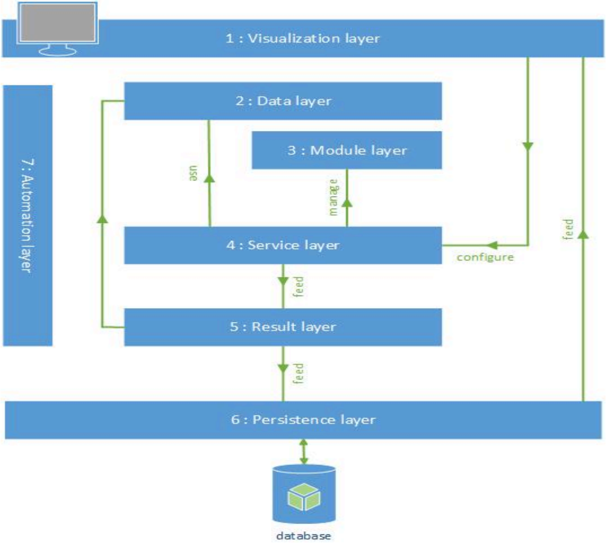
Experimental data collected at 3 facilities, soon 4 :EIC !

Sea quarks

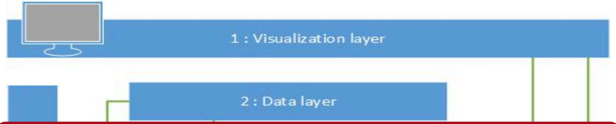


Gluons

NSAC, Long Range Plan 2015:
"We recommend [...] EIC as the highest priority for new facility construction"



PARtonic
Tomography
Of
Nucleon
Software



Preprint arXiv:1512.06174 [hep-ph]

- **Original approach** in fundamental research
- Inspired from **industrial codes**
- Two communities:
  users and **developers**
- Aggregation of **knowledge and know-how**:
  - Models
  - Measurements
  - Resolution techniques
  - Validation of each module

PARtonic
Tomography
Of
Nucleon
Software

A project with an international scope

Network of developers, upstream contributors and users

Multidisciplinary development team

Berthou	Binosi	Chouika	Guidal	Mezrag	Moutarde	Sabatié	Sznajder	Wagner
(Irfu)	(ECT*)	(Irfu)	(IPNO)	(ANL)	(Irfu)	(Irfu)	(IPNO)	(NCBJ)

IPN et LPT (Orsay), Irfu (Saclay) and CPhT (Polytechnique)

Experimental data analysis
World data fits
Perturbative QCD
GPD modeling

Commissariat à l'énergie atomique et aux énergies alternatives
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